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Formation and mechanical properties of bimodal microstructures in 0.2% carbon steel by heavy-reduction hot/warm compression

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Abstract

A compression test simulating heavy-reduction hot rolling was performed to investigate the compression behavior during the thermomechanical treatment and to systematically gather basic data on the formation of bimodal structures in 0.2% carbon steel at different deformation temperatures from 700 to 850 °C. The mechanical properties and the formation of such bimodal structures were revealed by field-emission scanning electron microscopy (FE-SEM), electron backscattering diffraction (EBSD) and tensile tests. Microstructures were considerably refined and equiaxed with higher fraction of high-angle grain boundaries when increasing deformation temperature from 700 to 850 °C. Especially, specimen compressed at 850 °C had average ferrite grain sizes of 1.4 μm and indicated high a likelihood of the formation of bimodal structure. Ultimate tensile strength and uniform elongation of this specimen were 677 MPa and 8%, respectively, which showed higher strength and twice improved uniform elongation than those of other specimens. Furthermore, their fractography showed dimples with less than 1 and 2-4 μm diameter on the fracture surface in 850 °C-compressed specimen, which indicated the bimodal-type dimple.

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Keywords: Steel; Bimodal structure; Dislocation; Thermomechanical processing; Plane-strain compression test

1. Introduction

For structural metals, intensive researches on severe plastic deformation process and grain refinement have been carried out to realize superior formability with higher strength over the last few decades, leading to reduction

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in the weight of products such as vehicles.

In the meantime, the intentional production of heterogeneous microstructures has been proposed to enhance ductility while retaining strength. In general, heterogeneous microstructure with coarse grains reduces mechanical properties, as represented by a bar with poor cold workability subjected to hot rolling by Yanagimoto et al. (2000). On the other hand, Wang et al. (2002) reported ductility was improved with keeping strength if coarse grains with micron-size (1-3 μm) was dispersed in a matrix of nanosize grains (<300 nm) in pure copper fabricated by annealing after multipass equal channel angular pressing. Since this discovery on high ductility while maintaining superior strength of heterogeneous fine-grained microstructures (so-called a bimodal structure), the bimodal structure in numerous metallic materials has been actively investigated by Witkin et al. (2003), Wang et al. (2008), Zhao et al. (2008), and Zhao et al. (2011). Most previous works have been concentrated on producing a bimodal structure in metals by annealing after multipass severe plastic deformation in cold or warm states, indicating the large power, high cost as well as long manufacturing time.

The aim of this study is to establish a manufacturing process for low-carbon steel sheets with a bimodal microstructure by single-pass thermomechanical processing. The formation process of the bimodal structure and the mechanism generating marked elongation in the bimodal structure are investigated by considering the microstructure obtained from plane-strain compression test and tensile tests.

2. Experimental procedure

Low-carbon steel with a composition of Fe-0.2C-0.53Mn-0.19Si-0.024P-0.014S-0.02Cr-0.01Ni in weight percent was used in this study. The as-received steel used had ferrite-pearlite phases with elongated structures in the rolling direction with an average ferrite grain size of 22 μm. As-received steel was machined into rectangular plates of $10\times50\times20$ mm^3 for the plane-strain compression test. The plane-strain compression test was carried out using a 150 kN compression testing machine (Yanagida et al., 2012). A schematic illustration of the compression testing machine is represented in Fig. 1. The critical transformation temperatures A_{c1} and A_{c3} for 0.2% carbon steel used were calculated to be 723 and 828 ^{o}C, respectively, by the empirical equations (Krauss, 2005). The samples were heated to target deformation temperatures of 700, 750, 800 and 850 ^{o}C at a rate of 10 ^{o}C/s by induction heating in N_2 gas atmosphere. Then the samples were kept at the deformation temperature for 20 s and compressed to a target thickness reduction of 70% ($t = 0.3t_0$) at a ram speed of 10 mm/s. After compression, the samples were immediately cooled by mist cooling at a rate of 20-30 ^{o}C/s. The as-received and compressed samples were machined into sheet-type tensile samples with a gage section of $10\times3\times1$ mm^3 (length×width×thickness) by wire-cut EDM. Tensile tests were performed on the samples at a strain rate of 1×10^{-3} s^{-1} at room temperature, and an extensometer (gage length of 10 mm) was connected directly to the tensile sample to accurately measure the strain during the tensile test. Field-emission scanning electron microscopy (FE-SEM) observation was performed to reveal the fracture surface characteristics on tensile tested samples after the tensile test. The samples were etched in 2% nital solution after mechanical polishing, and their microstructures were observed by optical microscopy (OM) and FE-SEM to investigate the microstructural evolution and orientation of selected samples. The grain size was determined by analyzing FE-SEM images.

3. Results and discussion

The resistance to deformation and the thickness strain in the plane-strain compression test were estimated using

$$K_{fm} = \frac{p}{wb}\,, \tag{1}$$

$$\varepsilon_t = \ln\frac{t_0}{t}\,, \tag{2}$$

where p, w and b are the load, sample width and punch width, and t_0 and t are the initial thickness and the thickness after compression, respectively (see Fig. 1).

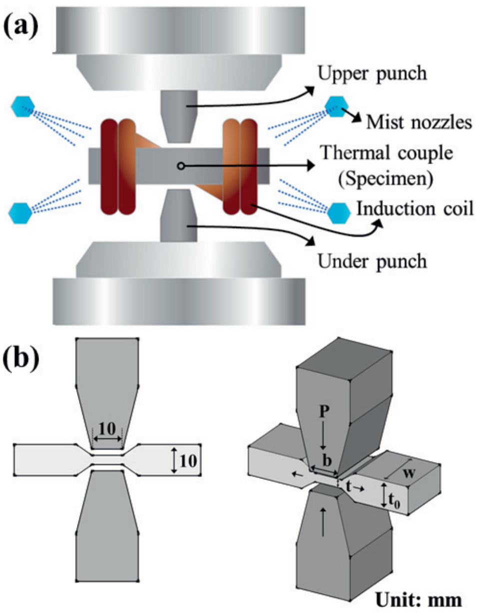

Fig. 1. Schematic illustration of compression testing machine; (a) compression equipment and (b) description of main parts in detail (Park and Yanagimoto, 2013).

Fig. 2 shows the resistance to deformation and thickness strain curves obtained in the compression test for different deformation temperatures. The yield strength and strain-hardening behavior changed significantly with increasing deformation temperature from 700 to 850 ^{o}C. The slope of the curves indicating strain-hardening reduces when the deformation temperature is increased. The resistances to deformation (K_{fm}) at r=70% for deformation temperatures of 700, 750, 800, and 850 ^{o}C are 1053, 765, 688, and 580 MPa, respectively. However, K_{fm} at r = 70% for deformation temperatures of 700 ^{o}C is estimated from the flow curve due to the limited compressive force of the machine. The values of K_{fm} for r = 70% at 800 and 850 ^{o}C, which are near A_{c3}, are expected to be about 40% less than that of the sample compressed at 700 ^{o}C, below A_{c1}. Note that this decrease in K_{fm} is imperative from an industrial viewpoint, because it reduces the rolling force and the energy used in the production process.

Referring to the curves in Fig. 2, the pressure should be carefully considered when conducting the rolling process. The contact length L_d can be calculated using $L_d = \sqrt{R(t_0 - t)}$, where R is the radius of the work roll. The rolling force P can be roughly estimated as

$$P = WL_d K_{fm} = WK_{fm}\sqrt{R(t_0 - t)}\,, \tag{3}$$

where W is the width of the strip after rolling. Substituting a deformation temperature of 850 ^{o}C, R = 360 mm and W=1000 mm into this equation, the rolling force P is about 28.2 MN/m or 2820 tons/m. Fortunately, this value is less than the maximum capacity of a hot strip rolling mill of approximately 30 MN/m.

The microstructures of the compressed specimens in the deformation regions for different deformation temperatures are shown in Fig. 3. The microstructures after deformation at 700 and 750 ^{o}C consisted of ferrite grains with pearlite colonies and ferrite-fine pearlite, and elongated structures. In Fig. 3(c), a fine ferrite-fine pearlite and elongated ferrite can be observed. At a deformation temperature of 850 ^{o}C, equiaxed fine ferrite and fine dispersed pearlite are present in addition to fine dispersed pearlite. The initial ferrite-pearlite structure transformed into a fine ferrite-fine dispersed pearlite structure, and the ferrite grain size was significantly refined with increasing the deformation temperature from 700 to 850 °C. Especially after deformation at 850 °C, the microstructure with an average grain size of 1.4 μm mainly consists of equiaxed fine grains (1-3 μm) with some ultrafine grains (<1 μm) in locals of the structure from the FE-SEM image in Fig. 4(a). Two Gaussian distributions can be observed in the distribution of grain size, as shown in Fig. 4(b). This result strongly indicates the formation of a bimodal structure by single-pass severe plastic deformation at a deformation temperature of 850 °C.

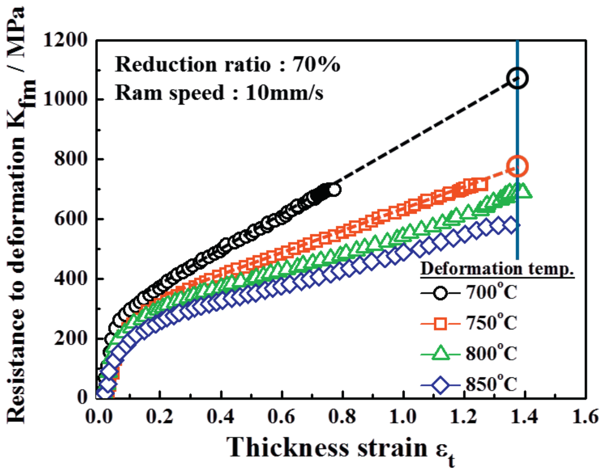

Fig. 2. Resistance to deformation and thickness strain curves obtained in the compression test for different deformation temperatures; dotted lines represent estimated K_{fm} at r = 70% ($t = 0.3t_0$) (Park and Yanagimoto, 2013).

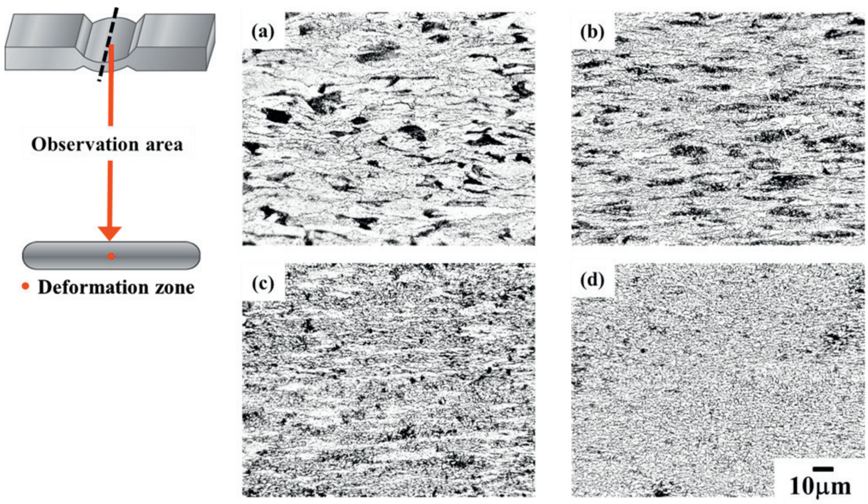

Fig. 3. Microstructures of the compressed specimens in the deformation regions for different deformation temperatures at (a) 700, (b) 750, (c) 800, and (d) 850 °C (Park and Yanagimoto, 2013).

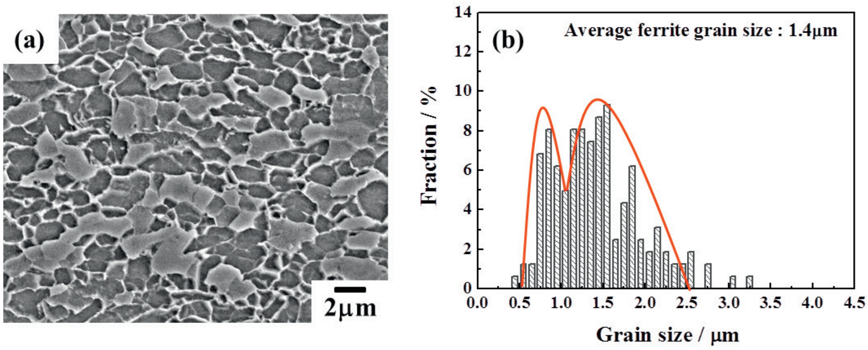

Fig. 4. SEM images and distributions of ferrite grain size of low-carbon steels in the compression test; (a) and (b) compressed at 850 ºC, GS_{ave} = 1.4 μm (Park and Yanagimoto, 2013).

Fig. 5 shows the changes in ultimate tensile strength and uniform elongation as functions of deformation temperature under the given conditions, where the average ultimate tensile strength and average uniform elongation are shown by solid symbols. Those of the plane-strain compression -tested samples were all enhanced from 600 to 720 MPa by thermomechanical treatment in comparison with the ultimate tensile strength of the as-received sample (about 550 MPa). The average uniform elongation of the samples was less than 5% of that of the as-received sample at a deformation temperature of up to 800 °C. However, the average uniform elongation improved to approximately 7-8% for the sample compressed at 850 °C, which was about twice higher than that of other samples. The deformation at 850 °C, above the critical temperature of transformation (A_{c3}), causes a significant increase in elongation. The heterogeneous microstructures with a mixed structure of submicron and micron-size grains were bimodal. Therefore, it can be concluded that the deformation above the critical temperature of transformation (A_{c3}) promoted the formation of bimodal structures and that all the samples exhibited superior elongation.

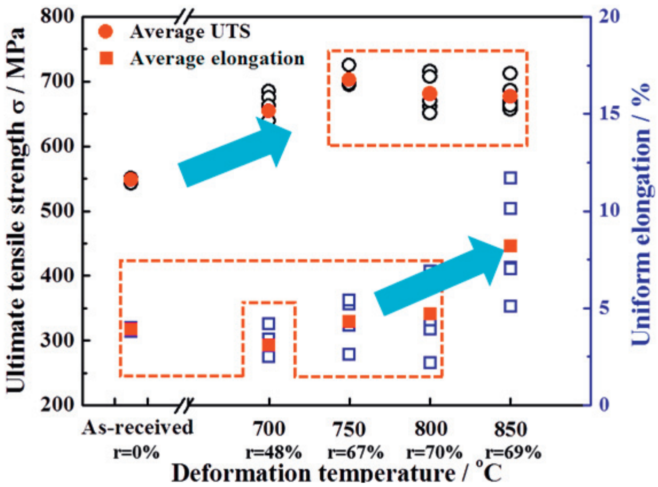

Fig. 5. Changes in ultimate tensile strength and uniform elongation as functions of deformation temperature under the given conditions (Park and Yanagimoto, 2013).

4. Conclusions

A plane-strain compression test realizing heavy-reduction single-pass rolling was performed to investigate deformation behavior and to collect preliminary data on the formation and mechanical properties of bimodal structures in 0.2% carbon steel. The major results are summarized as follows:

(1) The resistances to deformation (679 and 561 MPa respectively at r = 70%) upon compression at 800 and 850 ^{o}C are approximately 40% less than that (1028 MPa) upon warm forming at 700 ^{o}C.
(2) Average ferrite grain size after deformation at 850 ^{o}C was 1.4 μm. Two Gaussian distributions can be observed in the grain size distributions of these samples, indicating the possible formation of bimodal structures in 0.2% carbon steel by the plane-strain compression test.
(3) Average uniform elongation of the sample compressed at 850 ^{o}C was about 8%, which is nearly twice than those of the other samples. Additionally, on the fracture surface, a bimodal structure consisting of submicron-size (<1 μm) and fine (2-4 μm) dimples led to superior ductility while maintaining outstanding strength.

This proceeding is summarized by citing “Formation Process and Mechanical Properties of 0.2% Carbon Steel with Bimodal Microstructures Subjected to Heavy-Reduction Single-Pass Hot/Warm Compression” which was published in *Materials Science and Engineering A*.

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